

## Radar Investigation of Earth-Approaching Asteroids

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One of the remarkable discoveries of 20th century astronomy is that our planet resides in an asteroid swarm. Most of the nearly 200 known Earth-crossing asteroids (ECAs) have been discovered since 1986. The population probably includes (2000,  $3 \times 10^5$ ,  $15 \times 10^7$ ) objects with mean dimension  $\geq (1, 0.1, 0.01)$  km. Almost all ECAS are extremely difficult to study optically because of their small sizes -- they are dim and hardly ever subtend angles as large as 0.1 arcsec. However, much useful information about physical and dynamical properties can be obtained from radar observations of ECAS that come within reach of the Arecibo and Goldstone telescopes.

Resolution of echoes in Doppler frequency and/or time delay can be used to synthesize 1-D or 2-D images. Echo spectra are particularly useful for constraining spin vectors. Disc-integrated measurements also have value, because macroscopic radar wavelengths provide sensitivity to near-surface bulk density and structural scales larger than a few centimeters, and because metal, which is much more abundant in iron/stony-iron meteorites than in chondrites, influences radar reflectivity dramatically. Since delay/Doppler measurements are orthogonal to optical, angular-position measurements and often have much finer fractional precision, they permit significant improvement in estimates of orbits and hence in the accuracy of prediction ephemerides. For a newly discovered object, radar astrometry can help to ensure optical recovery during subsequent close approaches.

If the rotational-phase coverage is adequate and non-equatorial aspects are sampled, then delay-Doppler images can, in principle, be inverted to generate a model of the asteroid's 3-D shape. Such an inversion might incorporate parameters for spin vector components and for the delay-Doppler trajectory of the asteroid's center of mass.

Echoes from 30 ECAS have furnished new information about these objects' physical and dynamical properties. The reflectivity/polarization signatures of ECAS display striking diversity. 1986 DA is significantly more reflective than other radar-detected asteroids; it may be a piece of NiFe metal derived from the interior of a much larger object that melted, differentiated, cooled, and subsequently was disrupted in a catastrophic collision. A sequence of delay-Doppler images of 4179 Castalia (1989 PB) show it to consist of two kilometer-sized lobes in contact. Observations of 4179 Toutatis during Dec. 2-19 yielded daily delay-Doppler images placing hundreds to thousands of pixels on the asteroid, with delay resolution as fine as 0.125 microseconds (19 m) and fractional astrometric precision as fine as  $2 \times 10^{-9}$ . Toutatis has an unusual spin state and consists of two irregular, heavily cratered components in contact. Echoes from several other ECAs show evidence for shape bifurcation, so "contact binary" configurations may not be uncommon in the population.

Opportunities for radar investigation of ECAs will expand significantly upon completion of upgrades in the Arecibo and Goldstone instruments. Arecibo alone should be able to produce thousand-pixel images of several ECAs each year. A dedicated optical search program (e.g., the proposed Spaceguard Survey) could discover some 100,000 ECAs, most of which would traverse the Arecibo/Goldstone radar windows at least once every few decades.